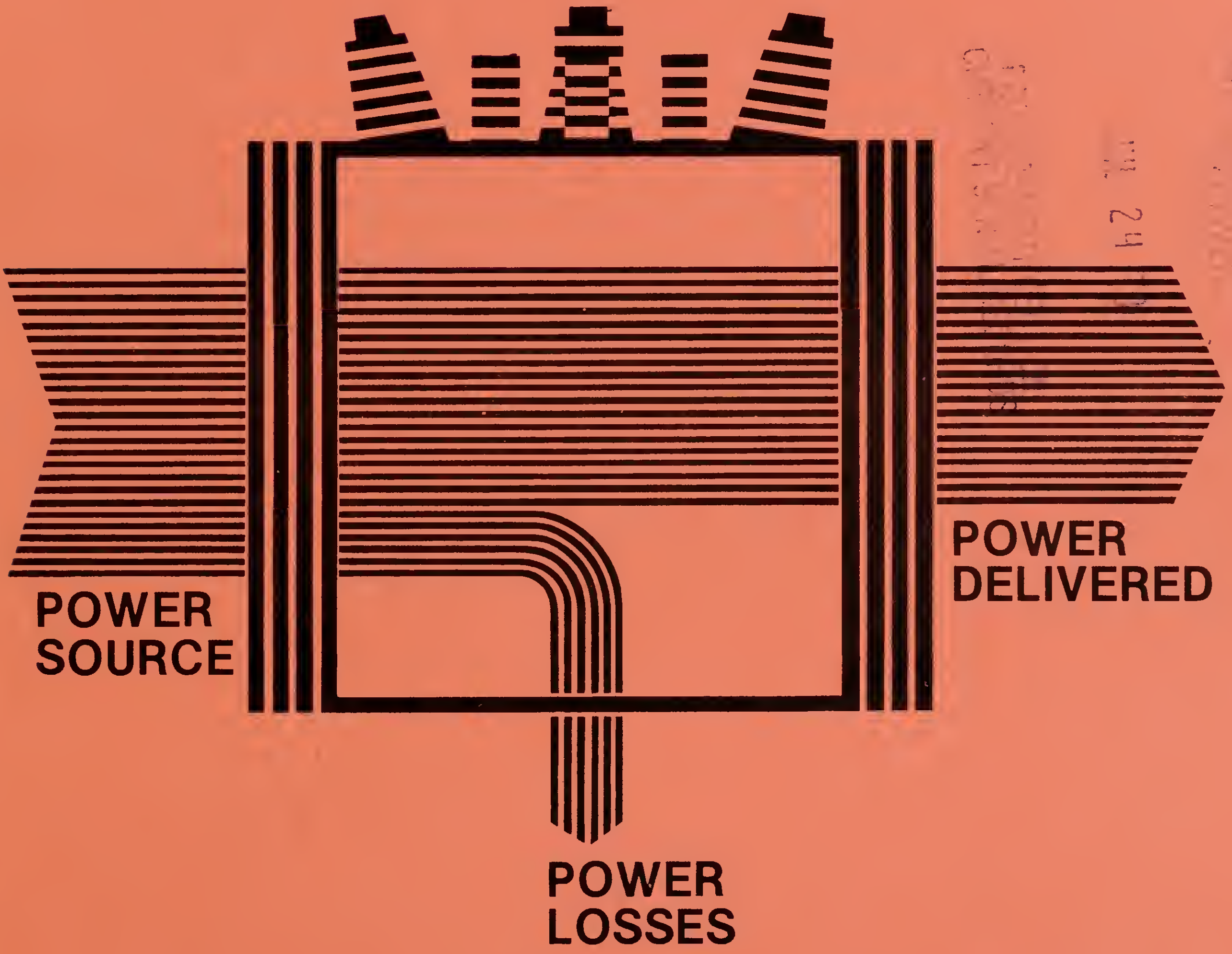
EVALUATION OF LARGE POWER TRANSFORMER LOSSES



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I. INTRODUCTION

When deciding which transformer to purchase, losses as well as the purchase price should be considered. One way of taking into account transformer losses is to assign a dollar value to the losses over the life of the transformer and to add this amount to the purchase price of the transformer. The purpose of this bulletin is to present a uniform approach that can be used to determine the dollar value of these losses. Given below is typical wording of a transformer loss evaluation clause for insertion into bidding documents to specify to the bidders how losses will be evaluated.

> *"Load, no-load, and auxiliary losses at 50 MVA for the 30/40/50 MVA transformer will be evaluated as follows:*
>
> | *No-Load Core Losses* | *Load (Copper) Losses* | *Auxiliary Losses* |
> |---|---|---|
> | *\$/kW 1790* | *\$/kW 1077* | *\$/kW 740* |
>
> *Evaluated losses for each transformer will be calculated by multiplying the appropriate dollars/kW values listed in the above table by the guaranteed load losses at 55°C rating and no-load losses at 100% voltage as stated in the appropriate spaces with the products added to the bid price for evaluation."*

A. Example

Using the loss evaluation factors given above, determine which manufacturer's transformer has the lowest evaluated cost including losses.

161/34.5 kV   30/40/50 MVA Transformer

	Manufacturer A's Transformer	Manufacturer B's Transformer
Bid price	\$424,500	\$436,000
No load losses	59 kW	53 kW
Load losses at 50 MVA, 55°C temperature rise	224 kW	218 kW
Auxiliary losses at 50 MVA, 55°C temperature rise	2.0 kW	2.5 kW

B. Solution

	A		B
Bid price		$424,500		$436,000
Total cost of no-load losses	59 kW(1790 $/kW) =	$105,610	53 kW(1790 $/kW) =	$ 94,870
Total cost of load losses	224 kW(1077 $/kW) =	$241,248	218 kW(1077 $/kW) =	$234,786
Total cost of auxiliary losses	2.0 kW(740 $/kW) =	$ 1,480	2.5 kW(740 $/kW) =	$ 1,850
TOTAL		$772,838		$767,506

The transformer for Manufacturer B has the lowest total cost.

In addition to giving loss evaluation values, the bid documents should also have penalty values that the manufacturer is to be charged for every kilowatt by which the actual tested transformer losses exceed the guaranteed losses upon which the bids are evaluated. It is important to have such penalty values in order to give an incentive to the manufacturers to provide as accurate guaranteed loss values as possible. The penalty values should be expressed in the same manner as the bid evaluation values and should be somewhat higher. An increment of approximately 20 percent is recommended.

II. FORMULAE

As indicated above, there are three different types of losses that must be evaluated separately. They are:

a. Load losses (sometimes called copper or coil losses);

b. No-load losses (sometimes called core or iron losses);

c. Auxiliary losses.

Load losses are the I^2R losses in the transformer windings, eddy current losses; and other similar losses that vary with load current. If a value of load losses is not directly given, it can be determined by subtracting no-load losses from total losses.* No-load losses consist

*If the total losses at full load are 100 kW and the no-load losses are 10 kW, then the load (or copper or coil) losses are 90 kW.

of the hysteresis and the eddy current losses in the iron core of the transformer and the I^2R losses in the windings due to the excitation current. Auxiliary losses consist of the power necessary to drive the auxiliary cooling pumps and fans.

The formulae below yield the total value of the losses in dollars that should be added to the purchase price of the transformer as shown in the example above so that losses can be properly taken into account.*

$$\text{Cost of no-load losses in dollars} = \left[SI + \frac{8760(EC)}{CC}\right]TNLL \qquad \text{(Eq. 1)}$$

$$\text{Cost of load losses in dollars} = \left[SI(K^2)(G) + \frac{8760(EC)(LFT)(G)}{CC}\right]TLL \qquad \text{(Eq. 2)}$$

$$\text{Cost of auxiliary losses in dollars} = \left[SI(K^2) + \frac{8760(EC)(LFA)}{CC}\right]TAL \qquad \text{(Eq. 3)}$$

where:

SI = the system capital investment in dollars per kilowatt required to supply the power losses of the transformer;

8760 = the number of hours in a year;

EC = the cost of energy in dollars per kilowatt-hour;

CC = the capital investment carrying charge expressed as a decimal in dollars per dollar of investment;

LFT = the transformer loss factor which is the ratio of average transformer losses to peak transformer losses;

G = the peak ratio which is the ratio of peak losses to losses at rated load;

K = the peak responsibility factor which is the ratio of transformer load at the time of the system peak to the transformer peak load;

*For derivation of equations see Reference 4.

LFA = the loss factor for the auxiliary equipment;

TNLL = the transformer's guaranteed no-load losses in kilowatts;

TLL = the transformer's guaranteed load losses in kilowatts;

TAS = the losses due to transformer auxiliary equipment in kilowatts.

A detailed discussion of the factors in equations 1 through 3 follows in the section below.

III. VALUES FOR FORMULAE

A. SI

The system investment charge represents the dollar investment in generation and transmission facilities per kilowatt necessary to supply the additional demand resulting from the transformer losses at the system peak. Since a transformer located directly at a generating station will not require an investment in transmission facilities, the SI value used to evaluate the losses in the generating station transformer should be less than the SI of a transformer to be located at the receiving end of a transmission line.

There are several methods for evaluating the SI value. One method is to use the construction costs per kilowatt of a recently completed or soon to be completed generating station and add to them a dollar per kilowatt value for any transmission facilities required to connect the transformer to the plant. If power is purchased rather than self-generated, the SI value can be determined by dividing the demand charge in dollars per kW per year by the carrying charge rate (CC). Since there is more than one method of evaluating SI, the method that is judged to yield the most realistic results should be used.

B. CC

The carrying charge rate (sometimes called the fixed charge rate) represents the yearly income necessary to support a capital investment, expressed as a percentage of capital investment. The rate is meant to cover all costs that are fixed and that do not vary with the amount of energy produced. The rate includes interest, depreciation, taxes, insurance, and those operation

and maintenance expenses that do not depend on system kilowatt-hours sold. The practice of including some operation and maintenance expenses in the fixed charge rate is not entirely universal and is, to some extent, a matter of judgement as to what is a better treatment. Some typical values for the components of the carrying charge rate are as follows:

Interest	7.50%
Depreciation	2.75%
Insurance	0.60%
Taxes	1.00%
Operation and Maintenance	2.76%
Carrying Charge Rate	14.61%

C. EC

The energy charge is the dollar per kilowatt-hour value that reflects those costs, such as fuel costs, that are directly related to the production of electrical energy. Although the costs per kilowatt-hour will vary with the level of demand, a single energy change representing an average cost per kilowatt-hour throughout the load cycle should be used for the sake of simplicity. Equations 1 and 2 are based on the assumption that the energy charge remains constant throughout the life of the transformer. See section IV for a discussion of the effects of inflation and increasing costs on the energy charge.

D. K

The peak responsibility factor is intended to compensate for the fact that the transformer peak load losses will not necessarily occur at the system peak losses. This means that only a fraction of the peak transformer losses will contribute to the system peak demand. The value of K can be determined from:

$$\text{Peak responsibility factor (K)} = \frac{\text{Transformer load at time of system peak}}{\text{Transformer peak load}} \qquad \text{(Eq. 4)}$$

It should be pointed out that K is squared in equations 2 and 3 because K is a ratio of loads while losses are proportional to the load squared. Any value of K that seems appropriate can be used. The following are recommended values that appear to be reasonable.

Transformer Type	K	K^2
Generator step-up	1.0	1.00
Transmission substation	0.9	0.81
Distribution substation	0.8	0.64

E. LFT

The transformer loss factor is defined as the ratio of the average transformer losses to the peak transformer losses during a specific period of time. For the sake of simplicity the equations are based on the assumption that the transformer loss factor is a constant and that it does not change significantly over the life of the transformer.

The transformer loss factor can be determined directly using the equation:

$$\text{Transformer loss factor (LFT)} = \frac{\text{kW-hours of loss during a specified time period}}{\text{(Hours)(Peak loss in kW in this period)}} \qquad \text{(Eq. 5)}$$

It can also be approximated from the load factor (the average load divided by the peak load for a specified time period) using the emperical equation below:

$$\text{Transformer loss factor (LFT)} = .7(\text{load factor})^2 + .3(\text{load factor})^* \qquad \text{(Eq. 6)}$$

*Load factor is the ratio of the average load over a period of time to the peak load occurring in that period. The load factor is a commonly available system parameter.

1. Example

Determine the transformer loss factor for a substation transformer that has a load factor of 47 percent.

2. Solution

$$\text{Transformer loss factor} = .7(.47)^2 + .3(.47)$$

$$\text{Transformer loss factor} = .296$$

F. G

The peak ratio is defined by the equation:

$$\text{Peak ratio (G)} = \left(\frac{\text{Peak annual transformer load*}}{\text{Full rated transformer load}}\right)^2 \qquad \text{(Eq. 7)}$$

The purpose of the peak ratio is to relate the value of equation 2 to the full rated transformer load instead of to the peak transformer load that would otherwise result if G were not in the equation.

The equation above is based on the assumption that the peak annual transformer load remains the same throughout the life of the transformer. The question then arises as to how does one handle the more realistic situation where the peak load grows by a given percentage every year. To answer this question, we must keep in mind what we are trying to accomplish, which is to arrive at a dollar value to assign to losses that in turn will enable us to choose the transformer that will be the least expensive in the long run, and not to exactly model the pattern of future transformer losses. Therefore, for the sake of determining the least costly alternative, we should use a reasonable equivalent level yearly peak loading value even though the expected peak loading value will increase every year. One way of determining a "reasonable" level peak load value is simply to choose one based on experience and judgement. Another method is to calculate a value using equation 13 which is explained and derived in Appendix A. The equation yields an equivalent level load that will result in the same total losses as the actual non-level loading pattern.

G. LFA

The auxiliary loss factor compensates for the fact that auxiliaries will be operating during only part of the transformer's load cycle. For a transformer with two stages of cooling:

*The one-hour integrated peak value should be used.

$$LFA = (.5)(\text{the probability that the first stage of cooling will be on at any given time}) \; + $$

$$(.5)(\text{the probability that the second stage of cooling will be on at any given time}) \qquad \text{(Eq. 8)}$$

The choice of the proper probabilities in the above equation is a matter of judgement based on historical system loading patterns. It is expected that the above probabilities under normal loading patterns will be extremely low and, in fact, it may be most reasonable to ignore the energy losses associated with transformer auxiliaries since it is unlikely that the extremely small amount of energy used by the auxiliaries over the life of the transformer could make a difference in the choice of a transformer. The capital cost associated with auxiliaries may, however, be more significant and should be considered.

IV. INFLATION

The problem of properly dealing with inflation in economic studies is a difficult and complex topic that is frequently not properly understood. The purpose of this section is not to provide an indepth analysis of the subject but rather to provide some general guidelines.

One method of handling inflation would be to increase future variable costs, such as the costs of losses, by the percentage represented by the general inflation rate. Since equations 1, 2, and 3 do not have any provisions for costs that increase over the years, an equivalent level cost that takes into account future cost increases must be used. The equation below will yield such a value and can be used in an attempt to adjust for inflation. (See Appendix B for derivation.)

$$A' = AX\left[\frac{1 - X^n}{1 - X}\right]\left[\frac{i(1 + i)^n}{(1 + i)^n - 1}\right]^* \qquad \text{(Eq. 9)}$$

where:

$$X = (1 + r)/(1 + i) \text{ for } r \neq i \qquad \text{(Eq. 10)}$$

A' = the cost adjusted for inflation

A = the base cost before inflation

*The term $\left[\frac{(1 + i)^n}{(1 + i)^n - 1}\right]$ is called the capital recovery factor and tables for determining it are easily available in most standard engineering economy texts.

n = the number of years in the inflation period. It is recommended that n be taken as 35 years which is the assumed transformer life. By assuming an n equal to the life of the transformer, an implicit assumption is being made that inflation will continue throughout the life of the transformer.

i = the time value of money per year expressed as a decimal

r = the rate of inflation per year expressed as a decimal

While the above method increases future costs, it fails to take into account the fact that the value of money is decreasing with inflation. It will "hurt" less to pay $100 ten years from now than it will today because it will take a person less time at the same job to earn $100.

Another and somewhat more realistic method of handling inflation is to assume that the increase of costs in the future will be balanced out by the decrease in the value of money, thus allowing us to ignore inflation altogether.* The problem with this approach is that the assumption does not always hold true because costs of certain items may increase faster than the general inflation rate. A third method of treating inflation that appears more realistic than the two methods mentioned above is to compensate both for the increase in costs associated with the generation and transmission of electric power and for the decrease in the value of the dollar due to the generally prevailing inflation rate. This compensation can be accomplished by coming up with an "equivalent inflation rate" (r') that could be used in equations 9 and 10. The exact formula for the equivalent rate is:

$$r' = \left[\left(\frac{1 + P}{1 + ig}\right) - 1\right] \quad \text{for } P \geq ig \qquad \text{(Eq. 11)}$$

where:

r' = the equivalent inflation rate

P = the rate of increase in costs per kWh associated with power generation and transmission expressed as a decimal

ig = the inflation rate for the economy as a whole expressed as a decimal.

The approximate form of the equation above is:

$$r' = P - ig \qquad \text{(Eq. 12)}$$

*See Reference 9, pages 260 to 269, for discussion of this point.

A. Example 1

Find the factor by which the energy charge rate must be adjusted to compensate for inflation if the following factors apply:

- General inflation rate (ig) = 5%
- Rate of increase of generating costs per kWh (P) = 5%
- Time value of money (i) = 7%

B. Solution

Solving for the equivalent inflation rate:

$$r' = \left(\frac{1 + P}{1 + ig}\right) - 1$$

$$r' = \left(\frac{1 + .05}{1 + .05}\right) - 1 = 0$$

Solving equation 4 for r' = 0, we get:

$$X = \left(\frac{1 + 0}{1 + i}\right) = \left(\frac{1}{1 + i}\right)$$

$$A' = A\left(\frac{1}{1+i}\right)\left[\frac{1-\left(\frac{1}{1+i}\right)^n}{1-\frac{1}{1+i}}\right]\left[\frac{i\,(1+i)^n}{(1+i)^n-1}\right]$$

$$A' = A\left(\frac{1}{1+i}\right)\left[\frac{(1+i)^n-1\;(1+i)}{(1+i)^n i}\right]\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$$

$$A' = A$$

Thus, the factor is 1. The above result was to be expected. Since the general inflation rate can be taken to be the rate at which the value of money decreases and since for this case it is equal to the rate of increase in costs, the two factors can be considered to cancel one another out and inflation can be ignored.

C. Example 2

Find the factor by which the energy charge rate must be adjusted to compensate for inflation if the following factors apply:

- General inflation rate (ig) = 5%
- Rate of increase of generating costs per kWh (P) = 6.5%
- Time value of money (i) = 8%

D. Solution

Solving for the equivalent inflation rate:

Equation 11 (exact): $r' = \left(\frac{1+P}{1+ig}\right) - 1 = \left(\frac{1+.065}{1+.05}\right) - 1 = .0143$

Equation 12 (approximate): $r' = P - ig = .065 - .05 = .015$

Solving equation 9 for r = .0143, n = 35 years:

$$x = \frac{1 + .0143}{1 + .08} = .9392$$

From tables, the capital recovery factor for i = 8%, n = 35 years, is .08580.

$$A' = A(.9392)\left(\frac{1 - (.9392)^{35}}{1 - .9392}\right)(.08580)$$

$$A' = A(1.178)$$

In general, the key to properly accounting for inflation in economic studies is to realize that inflation increases not only dollar costs but decreases the value of the dollar and affects all other factors that are related to money and/or the time value of money.

V. EXAMPLE

A 161/34.5 kV transformer rated at 30/40/50 MVA is to be purchased. It is to be put into a substation located at the end of a 80-mile transmission line. Determine the load, no-load, and auxiliary loss evaluation values in dollars per kilowatt of the guaranteed losses at the 50 MVA rating.

Assume:

- Capital cost of power plant is $1,000/kW.
- Capital cost of line and associated facilities is $130/kW.
- Average energy cost is $.01/kWh.

- Carrying charge rate is 14.6%.
- Time value of money is 9%.
- Load factor will stay at a constant value of 53% throughout the life of the transformer.
- Annual peak load will remain constant at a value of 53 MVA.
- Non-capital costs associated with generation and transmission increase at 5% per year.
- General inflation rate is 4%.

The solution would be:

A. The first step is to adjust the energy charge for the difference between the general inflation rate and the inflation of costs.

Thus, the energy charge adjusted for inflation:

$$EC' = EC(X)\left(\frac{1 - X^n}{1 - X}\right)\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right)$$

$$X = \left(\frac{1 + r}{1 + i}\right)$$

Adjusted inflation rate:

$$r' = p - ig = 5 - 4 = 1\%$$

$$X = \left(\frac{1 + .01}{1 + .09}\right) = .927$$

Assuming that inflation will continue into the unforeseeable future, a value of n = 35 will be used, as 35 years is the assumed life of a transformer.

$$EC' = EC(.927)\left(\frac{1 - .927^{35}}{1 - .927}\right)\left(\frac{.09(1+.09)^{35}}{(1+.09)^n - 1}\right)$$

$$EC' = EC(.927)(12.73)(.0946)$$

$$EC' = \left(\frac{\$.01}{kWh}\right)(.927)(12.73)(.0946)$$

$$EC' = \frac{\$.011}{kWh}$$

B. The system capital investment is equal to the cost of the plant plus the cost of transmission and associated facilities, all per kW; thus:

$$SI = \$1,000/kW + \$130/kW = \$1,130\ kW$$

C. Solving equation 1 for the cost of no-load losses in dollars per kilowatt of losses:

$$\text{Cost of no-load losses in dollars per kW of loss} = SI + \frac{3760(EC)}{CC}$$

$$= 1130 + \frac{8760(.011)}{.146}$$

$$= \$1790/kW \text{ of no-load loss}$$

D. Solving equation 2 for the cost of the load losses in dollars per kilowatt of losses:

$$\text{Cost of load losses in dollars per kW of loss} = (SI)(K^2)(G) + \frac{8760(EC)(LFT)(G)}{CC}$$

According to Section III, a peak responsibility factor (K) of .8 would be appropriate.

The peak ratio:

$$G = \left(\frac{\text{peak annual transformer load}}{\text{full rated transformer load}}\right)^2$$

$$G = \left(\frac{53\ MVA}{50\ MVA}\right)^2 = 1.124$$

Transformer loss factor:

$$LFT = .7(.53)^2 + .3(.53)$$

$$LFT = .356$$

$$\text{Cost of load losses in dollars per kW of loss} = 1130(.8^2)(1.124) + \frac{8760(.011)(.356)(1.124)}{.146}$$

$$= \$1077/\text{kW of load losses at 50 MVA}$$

E. Solving equation 3 for the cost of the auxiliary losses:

$$\text{Cost of auxiliary losses per kW of loss} = SI(K^2) + \frac{8760(EC)(LFA)}{CC}$$

From the system loading pattern, it is judged that the probability that the first stage of cooling will be on at any one time is .04 and that the probability that the second stage of cooling at any one time is .01. Thus, the loss factor for the auxiliary equipment is:

$$LFA = .5(.04) + .5(.01)$$

$$LFA = .025$$

$$\text{Cost of auxiliary losses} = 1130(.8^2) + \frac{8760(.011)(.025)}{.146}$$

$$\text{Cost of auxiliary losses} = \$723 + 16.5$$

$$\text{Cost of auxiliary losses} = \$740/\text{kW of auxiliary losses with all auxiliaries going}$$

The three loss values are:

No-Load Core Losses	Load (Copper) Losses	Auxiliary Losses
$1,790/kW	$1,077/kW	$740/kW

The factors above are those used in evaluating two transformers in the example in Section I.

VI. CONCLUSIONS

This bulletin provides a standard method and set of formulae for determining what values of losses shall be used in transformer evaluation. It should be emphasized, however, that there will always be a great deal of judgement involved in using the formulae.

Assistant Administrator - Electric

Attachments:
APPENDIX A - EQUIVALENT LEVEL LOAD FORMULA
APPENDIX B - DERIVATION OF EQUATION 9
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APPENDIX A

Equivalent Level Load Formula

It is assumed that the load on the transformer is initially Y_1, it increases at a rate of k percent per year, and when the load reaches Y_2, the transformer is either charged out or a second transformer is put in. It is further assumed that this pattern continues for the life of the transformer.

To get the equivalent level load, we first must determine an equivalent level loss value that results in the same total losses as the yearly increasing load; then this loss value can be equated to a load.

Let:

k = the rate of growth of the load, expressed as a decimal

Y_1 = the ratio of load to capacity when transformer is installed

Y_2 = the ratio of load to capacity when transformer is removed

t = time in years that it takes for load to grow from Y_1 to Y_2.

If it is assumed that the load growth cycle on the transformer is repeated throughout its life, then we need only get the equivalent level load for one cycle.

Since losses are proportional to the square of the load:

$$LS = \frac{a\int_0^t Y_1^2(1 + k)^{2n}dn}{t} \qquad \text{(a)}$$

LS = equivalent level losses

n = time in years

a = proportionality factor between losses and load such that:

$$LS = a(\text{load})^2 \qquad \text{(b)}$$

Solving equation a:

$$LS = aY_1^2 \frac{(1 + k)^{2t} - 1}{2t \ln (1 + k)} \qquad \text{(c)}$$

Combining b and c to get equivalent level load:

$$\text{Equivalent level peak load} = Y_1 \sqrt{\frac{(1 + k)^{2t} - 1}{\ln(1 + k)^{2t}}} \qquad \text{(Eq. 13)}$$

Derivation for t:

$$Y_2 = Y_1(1 + k)^t \qquad \text{(d)}$$

$$\frac{Y_2}{Y_1} = (1 + k)^t$$

$$\log \frac{Y_2}{Y_1} = t \log (1 + k)$$

$$t = \frac{\log\left(\frac{Y_2}{Y_1}\right)}{\log(1+k)} \qquad \text{(Eq. 14)}$$

If it cannot be assumed that the loading pattern on a transformer will be repeated throughout its life, the approach used in the derivation above can still be used. That is, determining an equivalent level loss value by dividing the integral of the square of the load curve by the time period involved.

Example

On a particular system a triple rated transformer is to be installed when the peak load is .95 of the OA rating. The load is assumed to grow at 8 percent per year. When the peak load reaches 1.9 of the on-rating an additional unit will be installed.

Assuming the above pattern will continue throughout the life of the transformer, determine the equivalent level peak load.

Solution

Using equation e:

$$t = \frac{\log\left(\frac{1.9}{.95}\right)}{\log(1 + .08)} = 9.0 \text{ years}$$

Using equation 13:

$$\text{Equivalent level peak load} = .95\sqrt{\frac{(1 + .08)^{2(9.0)} - 1}{(2)(9.0)\ln(1 + .08)}}$$

$$\text{Equivalent level peak load} = 1.40 \text{ of OA rating}$$

APPENDIX B

Derivation of Equation 9:

Equation 9 gives a level cost (or energy charge rate) that will yield the same total present worth value as a cost (or energy charge rate) that is increasing at "r" percent per year.

The present worth of a cost increasing at "r" percent per year is:

$$PW = A\left[\frac{(1 + r)}{(1 + i)} + \frac{(1 + r)^2}{(1 + i)^2} \cdot\cdot \frac{(1 + r)^n}{(1 + i)^n}\right] \qquad (g)$$

where:

- i = the time value of money
- r = the rate of inflation
- A = the cost before inflation
- PW = the present worth
- n = the time period in years

If we let $X = \left(\frac{1 + r}{1 + i}\right)$ (Eq. 10)

then:

$$PW = AX\,(1 + X + X^2 \ldots X^{n-1}) \qquad (h)$$

Doing some algebraic manipulation, we get:

$$PW = AX\left[\frac{1 - X^n}{1 - X}\right] \qquad (i)$$

Multiplying by the capital recovery factor to get an equivalent level yearly cost we have:

$$A' = AX\left[\frac{1 - X^n}{1 - X}\right]\left[\frac{i\,(1 + i)^n}{(1 + i)^n - 1}\right] \qquad \text{(Eq. 9)}$$

APPENDIX C

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